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Source: Natural Areas Journal, 37(3):332-349.
Published By: Natural Areas Association
https://doi.org/10.3375/043.037.0308
URL: http://www.bioone.org/doi/full/10.3375/043.037.0308

RESEARCH ARTICLE

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Acoustic Footprint of Snowmobile Noise and Natural Quiet Refugia in an Alaskan Wilderness

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Natural Areas Journal 37:332–349

ABSTRACT: Snowmobiling in Congressionally designated Wilderness (CW) in Alaska is a contentious issue in the arena of appropriate use of public lands. The 1980 Alaska National Interests Lands Conservation Act allows snowmobiling in CW for traditional activities. Conversely, the 1964 Wilderness Act prohibits motor vehicles in CW to preserve its naturalness and opportunities for solitude. These conflicting mandates challenge the ability of managers to preserve CW character. The Kenai National Wildlife Refuge (KENWR) manages 534,300 ha of CW, where 253,200 ha are open to snowmobiling. Snowmobile noise degrades CW character whereas natural quiet is indicative of naturalness and offers opportunities for solitude. We determined the acoustic footprint of snowmobile noise and areas of natural quiet refugia in CW by recording the soundscape at 27 locations inside, and 37 locations outside, KENWR CW. We calculated soundscape power (normalized watts/kHz) from 59,598 sound recordings and generated spatially explicit models of snowmobile noise and natural quiet using machine-learning (TreeNet). We calculated the area of CW with the highest and lowest soundscape power for snowmobile noise and natural quiet, respectively. Snowmobile noise occurred during daylight hours while natural quiet was predominant at night. Snowmobile noise was higher in February and March while January was quieter. Snowmobile noise affected 39% of CW open to snowmobiling while natural quiet made up 36%. Natural quiet occurred in 51% of all KENWR CW of which 39% was prohibited by management or inaccessible by snowmobiles. Our models identify areas where conservation of winter soundscapes in CW can be focused.

Index terms: Alaska National Interest Lands Conservation Act, snowmobile noise, soundscape, wilderness, Wilderness Act

INTRODUCTION

Advancements in mechanized transport have expanded the ecological footprint of human populations and enhanced our ability to access areas of the world never before explored or exploited, drastically altering the Earth's ecosystems (Vitousek et al. 1997). One result of these advancements is the industrialization of modern societies that has subsequently contributed to the augmentation of the world's human population (Zeira 2006). The extent of human impacts on the biosphere, driven by mechanization, may be significantly influencing the Earth's evolution into what Crutzen (2006) describes as the Anthropocene epoch.

Since invention of the steam locomotive and internal combustion engines in the 19th century, the United States population has grown from 7 million to more than 308 million (US Census Bureau 2010). Population growth and the sprawl of development and mechanization into more rural areas of the United States in the 1960s sparked an awareness of its potential to affect even remote parts of the country, including wild lands (McClosky 1966). In order to protect some of the country's more beautiful, pristine, and valuable landscapes, the US Congress enacted the Wilderness Act in 1964. Reflecting the spirit of democracy, this Act was specifically intended "to secure for the American people of present and future generations the benefits of an enduring resource of wilderness" (Section 2(a)).

The Wilderness Act defines Congressionally designated wilderness (CW) as having four distinct characteristics (Section 2(a)). Congressionally designated wilderness is recognized as an area (1) "where the earth and its community of life are untrammeled by man," (2) "of undeveloped Federal land retaining its primeval character and influence," (3) that "generally appears to have been affected primarily by the forces of nature," and (4) that provides "outstanding opportunities for solitude." Inherent in these definitions is the preservation of ecological processes that have shaped CW in the absence of the industrial and mechanized activities of man. This state of "naturalness" and untrammeled condition provide the foundations of CW areas. Equally, the human experience of CW is meant to contrast sharply with that of a machine-dominated and developed modern society.

The definitions outlined by the Wilderness Act differentiate CW from that of the diverse definitions of wilderness that stem from a variety of human perspectives. For example, wilderness may be viewed by some as the backcountry of public lands not designated as CW or private lands that do not fall within the mandates and definitions of the Wilderness Act. Conversely, wilderness to others may be as simple as a roadside picnic area or a wooded lot in their backyard. Individuals' interpretations, perceptions, and definitions of wilderness are as diverse as the individuals themselves (Nash 2014). The Wilderness Act attempts to consolidate these perspectives by defining CW as a conceptual resource (Farina 2012) designated with arbitrary boundaries and characteristics that can be sustained through preservation and management.

In contrast to the contiguous United States, Alaska is mostly undeveloped wild lands. In 1980, President Carter signed the Alaska National Interests Lands Conservation Act (ANILCA) to "preserve the unrivaled scenic and geological values associated with [Alaska's] natural landscapes" (Section 3101(b)). More than 42 million ha of new and expanded public land were established under ANILCA into 13 national parks, 17 national wildlife refuges, several scenic rivers, recreation areas, national monuments, and conservation areas; over half of these lands were designated as CW.

Alaska has a long history of traditions that are deeply rooted in ecological, cultural, and economic perspectives and practices (Ritter 1993; Wolfe 2004). Through ANILCA, federal land managers attempted to balance the national interests of Alaska's unique scenic and wildlife resources with that of Alaska's developing economy, infrastructure, and rural way of life (Public Law 96-487). As a result, ANILCA has specific provisions for motorized access into CW areas for "traditional activities" (Sections 1110(a) and 811(b)).

The Wilderness Act explicitly states that there shall be no use of motorized equipment, landing aircraft, use of motor vehicles, or other forms of mechanical transport except to meet minimum requirements for administration of the area (Section 4(c)). However, in instances where the use of aircraft or motorboats was previously established, such motorized vehicles are permitted (Section 4(d)(1)). Similarly, the provisions of ANILCA state that access on conservation system units (including CW) allows the use of snowmobiles for traditional activities and for travel to and from villages and homesites (Sections 1110(a)), as well as for subsistence purposes traditionally employed for such purposes by local residents (Section 811(b)).

The use of snowmobiles did not become commonplace until the 1970s, years after the Wilderness Act was legislated (Butler 1970). Snowmobiling has since served as a means of transportation to explore wilderness areas, as well as for hunting and trapping (Simpson 1987), all of which could be considered by some as traditional activities because they existed prior to ANILCA. However, traditional activities are neither defined by ANILCA nor are the conditions of the Wilderness Act redefined to include snowmobiling in Alaskan CW based on the same premise laid out for aircraft and motorboats. This can result in confusion when balancing the rights of snowmobilers and the compatible use of snowmobiles within CW that public land managers are required to determine and legally regulate to preserve its character (Tranel 2001).

Sound is an innate component of ecological systems and is essential for animal communication and habitat selection, as well as for human enjoyment of nature (Mace et al. 1999, 2004; Slabbekoorn and Bouton 2008; Lillis et al. 2013; Farina 2014). The sounds that emanate throughout the landscape (i.e., soundscape) are, therefore, essential elements of CW. Three components of a soundscape are biological sounds (biophony) (Krause 1998, 2001, 2002), geophysical sounds (geophony) (Qi et al. 2008; Pijanowski et al. 2011; Farina 2014), and anthropogenic mechanical sounds (technophony) (Gage and Axel 2014; Mullet et al. 2016). Snowmobiles and other motorized transports (e.g., aircraft, automobiles, motorboats) emit low-frequency technophony that can propagate over long distances and through vegetation (Bashir et al. 2015), thereby creating an acoustic footprint well beyond its source (Barber et al. 2010). As a result, the technophony produced by snowmobiles can significantly affect the CW characteristics of naturalness and opportunities for solitude (Simpson 1987; Barber et al. 2010; Harris et al. 2014; Farina 2014; Shannon et al. 2014).

Examples of these effects are the tendency of technophony to inhibit the propagation and interpretation of animal vocalizations (i.e., masking) and influence human perspectives of natural areas based on the composition of the soundscape (Carles et al. 1999; Truax 2001; Barber et al. 2010). Snowmobiles are known to have an audible tonal peak of 200 Hz and a sound pressure level of 9 dB at nearly 1 km from the source, 20 times louder than the lowest audible threshold of human hearing (Menge et al. 2002). At distances ≤15 m, snowmobiles can emit sound pressure levels ≥71 dB (Fussell 2002; Burson 2008) with peak frequencies >11 kHz (pers. obs.) (Figure 1). Common winter residents in Alaska like the Common Raven (*Corvus corax* L.) and Black-capped Chickadee (*Parus atricapillus* L.) vocalize at 250–1850 Hz (Conner 1985) and 3000–5000 Hz (Hill and Lein 1987), respectively. Because the frequency range of sounds emitted by snowmobiles overlaps with the vocalizations of these animals and others, snowmobiles have the potential to mask biophony, an effect known to alter normal animal behavior and natural processes (Figure 1) (Goodwin and Shriver 2010; Chan and Blumstein 2011; Ortega 2012; McClure et al. 2013). From a human perspective, technophony can deteriorate humans' sense of naturalness, whereas natural sounds induce states of relaxation and enhance perceptions of environmental quality (Bjork 1989, 1995; Carles et al. 1999).

Snowmobiles today are able to travel farther into more remote areas than they have since snowmobiles became popular and widely manufactured (Butler 1970; International Snowmobile Manufacturers Association 2015). Although snowmobiling can promote the use and appreciation of CW and other wild areas, the combination of high speed, rapid maneuverability, and loud noise make snowmobiling a conspicuous and alarming stimulus in the landscape (Mahoney et al. 2001). Like many other machine-generated sound sources (e.g., mining activity, aircraft, automobiles), the presence of snowmobiles and the acoustic footprint they create influence the distribution and composition

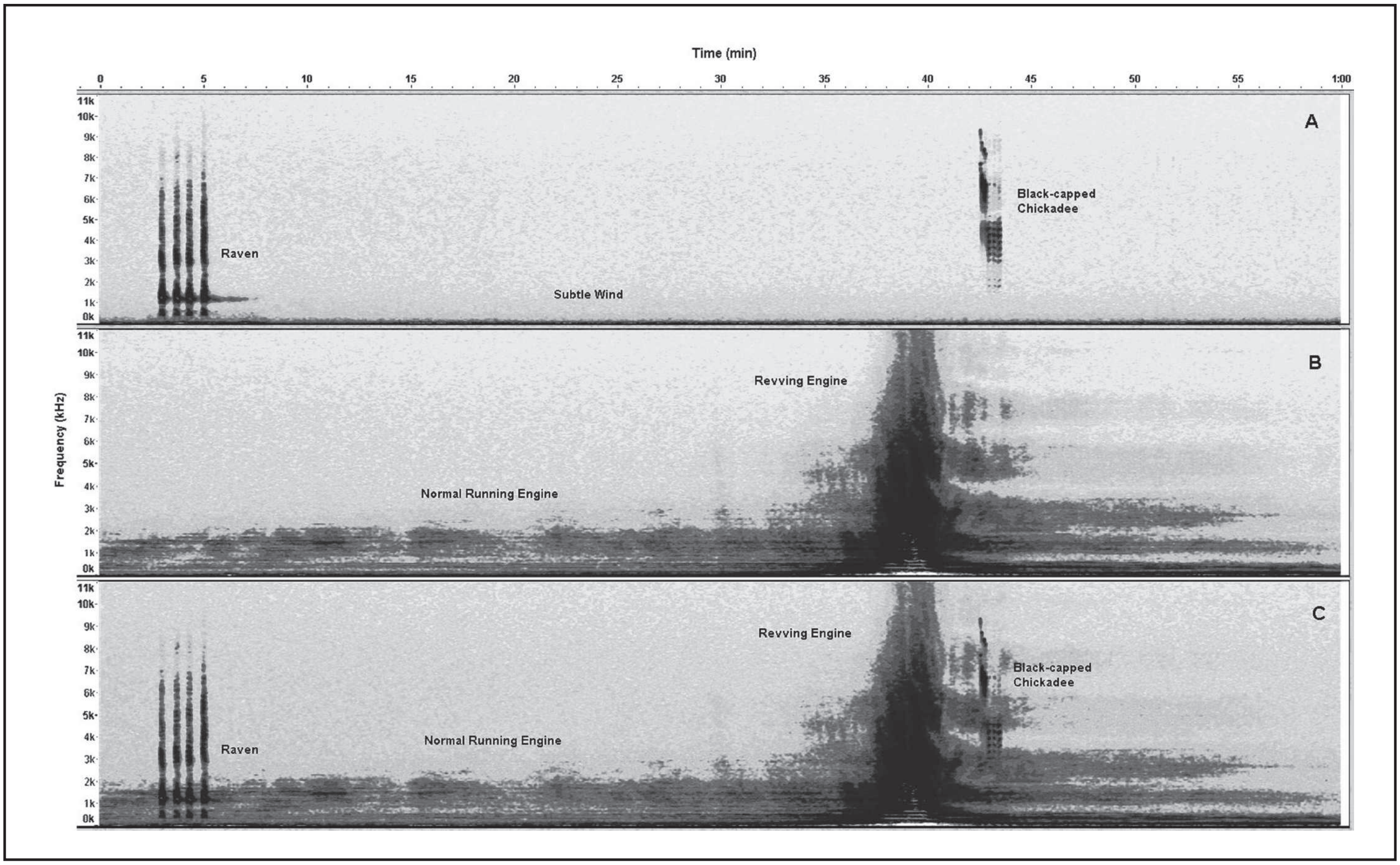

Figure 1. Spectrograms of the (A) variations in spectral distribution of three common natural quiet sound sources, (B) variations in spectral distribution of snowmobile noise, and (C) overlap of spectrograms A and B displaying potential effects of snowmobile noise masking natural quiet phenomena.

of sounds in nature (Duarte et al. 2015; Mullet et al. 2016). Hence, the sounds produced by snowmobiling can degrade and negatively affect CW resources and devalue human experience in CW settings, all of which contradict the purposes of the Wilderness Act. In these cases, we refer to the low-frequency sounds produced by machines (including snowmobiles) as noise in the context of unwanted sound based on human pursuits to experience natural quiet and its negative influence on wildlife behavior (Truax 1999).

The composition of soundscape components is linked to landscape characteristics (Mennitt et al. 2014; Mullet et al. 2016) and can indicate the quality of natural areas (Qi et al. 2008; Farina et al. 2011; Pieretti et al. 2011; Fuller et al. 2015). The detection and propagation of technophony emitted by snowmobiles throughout the landscape can reveal the spatial extent of human disturbance and degradation of CW character. In contrast to non-CW, it is expected that CW is dominated by natural sounds in the landscape that provide an uninhibited human experience of solitude and an unobstructed sonic environment for wildlife with the acoustic footprint of technophony substantially unnoticeable or absent.

To assess the impact that snowmobile noise has on CW character, we sought to identify the spatial extent of snowmobile noise (acoustic footprint) in an Alaskan CW and identify areas where natural quiet persistently dominates (acoustic refugia). Our objectives were to (1) sample the acoustic composition of an Alaskan soundscape in winter in the context of snowmobile noise and natural quiet, (2) describe the temporal variation and spatial distribution of snowmobile noise and natural quiet in CW, and (3) quantify the acoustic footprint of snowmobile noise and acoustic refugia of natural quiet within CW.

METHODS

Study Area

The acoustic effects of snowmobile noise on CW character are likely more prevalent in areas of Alaska where the human population is high and CW is easily accessible. The 805,000-ha Kenai National Wildlife Refuge (KENWR) is one of two national wildlife refuges in Alaska on the highway system and the only one with a significant urban interface (Figure 2). Located on the Kenai Peninsula in south-central Alaska, KENWR includes 534,300 ha of CW that is composed of the Dave Spencer, Mystery Creek, and Andrew Simons Wilderness Units (Figure 2).

The CW of KENWR encompasses some of the most diverse subarctic ecosystems in Alaska, including coastal wetlands, boreal

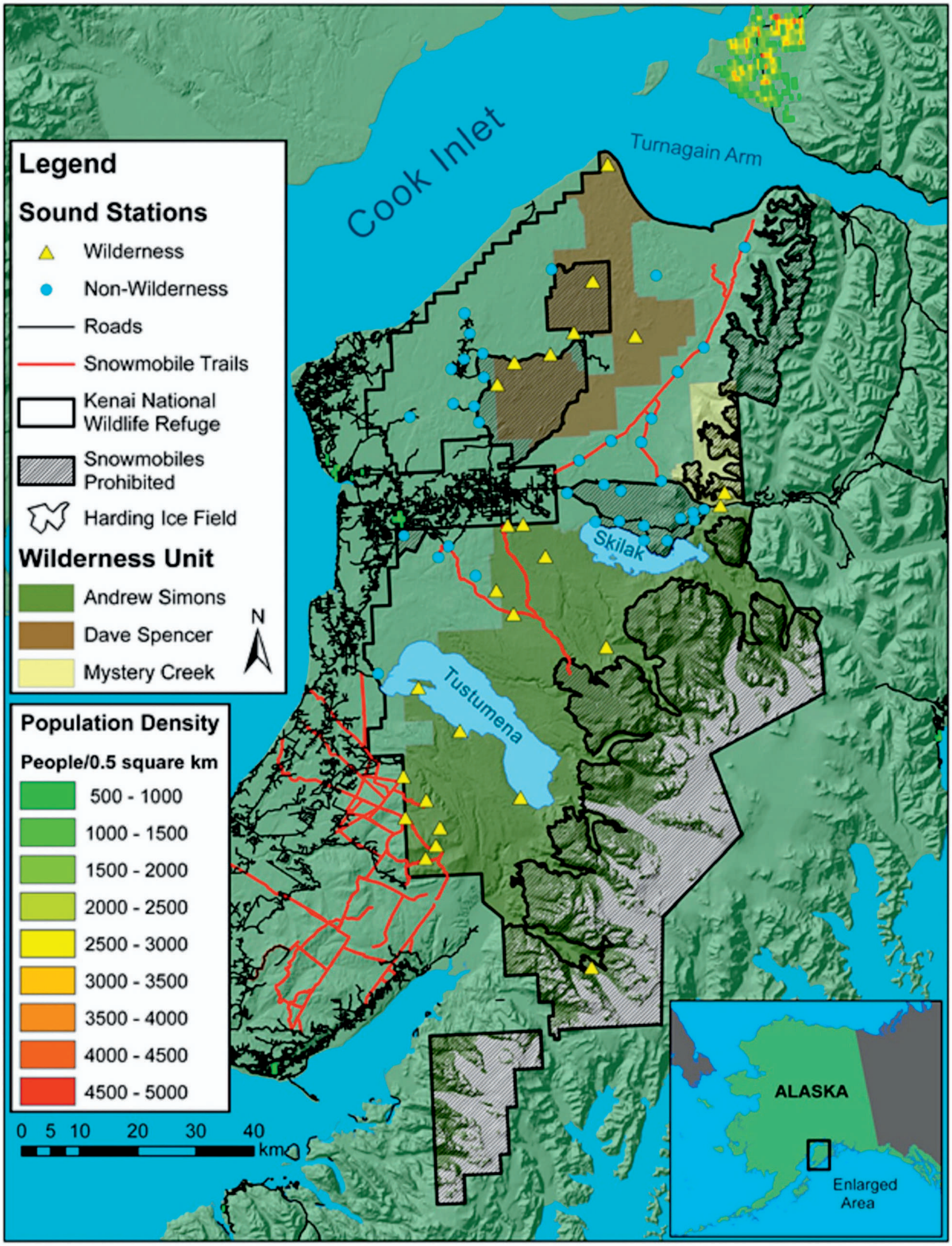

Figure 2. Geographic orientation of the Kenai National Wildlife Refuge, Alaska, and sound sampling stations in congressionally designated wilderness (n = 27) and non-wilderness (n = 37) in association with Wilderness Units, wilderness access features, areas where snowmobiling is prohibited, and population densities (>500 people/0.5 km^2) of towns and cities that are typical sources of snowmobilers that recreate in wilderness.

forests, alpine tundra, and over 106,000 ha of the Harding Ice Field. The KENWR's lowland forests are dominated by white spruce (*Picea glauca* (Moench) Voss) and black spruce (*P. mariana* (Mill.) Britton, Sterns, and Poggenb.) with a mixture of aspen (*Populus tremuloides* Michx), birch (*Betula neoalaskana* L.), and an extensive wetland network. Elevations range from sea level to 1800 m. Annual temperatures rarely exceed 26 °C in the summer or drop below −18 °C in the winter, although temperatures have been known to exceed these ranges. Annual precipitation ranges from 43 cm in the lowlands to 502 cm in the Kenai Mountains.

Summer is the most active season of the year on KENWR due to an increase in tourism when automobiles, aircraft, and motorboats can generate a large amount of technophony (KENWR Comprehensive Conservation Plan 2010). Although out-of-state tourism greatly decreases in winter, residents from both the Kenai Peninsula and Anchorage area recreate in KENWR. One of the most widespread winter activities and sources of technophony is snowmobiling (Mullet 2014). The KENWR currently allows snowmobiling access to 476,000 ha, 53% of which is CW (253,200 ha) (Figure 2) (West 2007). To reduce the impacts snowmobiling has on wildlife and the environment, KENWR established regulations that restricted the size of machines (<102 cm wide) and the type of use (e.g., no racing or road use), excluded alpine tundra in the Kenai Mountains to prevent vegetation damage, and restricted use in other areas between December and April, contingent on adequate snowpack to prevent vegetation damage.

Sound Sampling

We sampled the soundscape at 27 locations within CW and 37 locations outside of CW in KENWR (Figure 2). Our sample sites were wetlands, mixed coniferous forests, deciduous forests, frozen lakes, rivers, streams, alpine tundra, glacier, along roadsides and snowmobile trails, and oil and gas compressor sites. We recorded the latitude and longitude of each sample site allowing us to associate each sound record to a spatially explicit location in the landscape.

We recorded ambient sounds daily from December 2011 to April 2012 for 1 minute every 30 minutes using autonomous recorders (Song Meter SM2, Wildlife Acoustics Inc., Maynard, MA, USA). We recorded in monaural at 16 bits in a Waveform Audio File format (WAV) at a sample rate of 22,050 Hz for a total useable frequency range of 11 kHz. Due to a reduction in battery life as a result of cold temperatures ranging from −35 to 0 °C, we visited each sound recorder every 7–10 days to replace batteries and SD cards. Sound recorders were then set to continue recording to ensure a consistent sampling regime throughout the course of our study.

We uploaded and archived sound files into the Remote Environmental Assessment Laboratory's (REAL) digital sound library located at Michigan State University (http://www.real.msu.edu). The REAL library stores sound recordings, computes and displays soundscape metrics, and enables users to access and query soundscape information for analysis. Kasten et al. (2012) provide details on how REAL uploads, processes, archives, and accesses sound recordings and how it derives soundscape metrics. All recordings, spectrograms, sensor locations, photographs, raw data, metadata, and analysis options are open access and available online at http://real.msu.edu/projects/one_proj.php?proj=knwx.

We calculated the Power Spectral Density (PSD) of sound recordings using Welch's (1967) method in Matlab v16 (Mathworks Inc., Natick, MA, USA) and expressed our metrics in watts/kHz. We vector normalized PSD values (0–1) across ten 1-kHz frequency intervals (1–11 kHz) for each recording to compare soundscape power (normalized watts/kHz) across all 10 frequency intervals (Kasten et al. 2012). We selected this frequency range in order to eliminate excessive noise data below 1000 Hz and focus on the potential disturbance of natural quiet phenomena that typically occur ≥1000 Hz (Gage and Axel 2014; Mullet et al. 2016). Frequencies above 11 kHz are typically associated with species not present in our study area over winter (e.g., insects, bats).

Although soundscape power is not equivalent to sound pressure level (SPL), a metric widely used by the National Park Service (NPS), it is comparable to louder and quieter sound events but using different metrics. For instance, PSD, calculated for soundscape power, is the energy of a sound signal (e.g., watts) by frequency (e.g., kHz) within the acoustic space that can determine what frequency ranges have the lowest to highest sound energy: high energies being louder sounds and lower energies being quieter sounds (Welch 1967; Hansen 2001). To a similar extent, SPL is the level of sound pressure that deviates from the atmospheric pressure compared to a reference threshold, typically the audible sensitivity of the human ear measured in decibels (dB). High SPLs represent larger deviations from atmospheric pressure and are perceived as louder than lower SPLs (Hansen 2001). Both Mennitt et al. (2014) and Mullet et al. (2016) have supported the merits of each of these metrics in soundscape analysis and their significance in ecological systems.

We identified snowmobile noise and natural quiet by listening to and visualizing the spectrograms of 59,598 sound recordings (27,179 in CW; 32,419 in non-CW). We categorized sound recordings of natural quiet as those recordings of biophony (i.e., animal vocalizations) and geophony (e.g., subtle, distant breezes blowing through forested areas, the creaking of branches, ice cracking, falling snow or rain making contact with our microphones, trees, and the snow surface), as well as the complete absence of technophony.

Modeling Snowmobile Noise and Natural Quiet

We used the weighted average of soundscape power of snowmobile noise and natural quiet for each sound recording station and imported the coordinates of each sound station with their associated weighted averages into ArcGIS 10.2.1 (Esri, Redlands, CA, USA). Spatially explicit sound data were overlaid with 16 associated environmental layers for snowmobile noise and natural quiet using the Extract Multi Values to Points tool in ArcGIS Spatial Analyst (Table 1). Two of our environmental layers were predicted snowmobile activity (snowmobile tracks/0.06 km^2) and snow depth. These models were generated by methods outlined by Mullet (2014).

Mullet et al. (2016) have successfully applied the use of machine-learning to modeling and identifying acoustic–environmental relationships of soundscapes across large spatial scales and more specifically, to winter soundscapes in KENWR. A growing body of work has established supporting evidence that machine-learning algorithms (e.g., boosted regression trees, CART, RandomForests, TreeNet) are useful tools for quantifying the spatial distribution and landscape relationships of plants and animals (Guisan and Zimmermann 2000; Prasad et al. 2006; Craig and Huettmann 2009; Drew et al. 2011). Applying similar methods here, we modeled snowmobile noise and natural quiet soundscape power using stochastic gradient boosting (TreeNet) (Salford Predictive Modeler v7.0; Salford Systems Inc., San Diego, CA, USA). TreeNet uses machine-learning algorithms to build predictive models based on the relationships between target and predictor variables (e.g., distance to roads, distance to snowmobile trails). We generated partial dependence plots in TreeNet to identify the relationship between soundscape power and environmental variables (i.e., acoustic–environmental relationships) influencing the spatial distribution of snowmobile noise and natural quiet.

To create a spatial map of model predictions, we scored acoustic–environmental relationships learned in TreeNet to a regular 0.25-km^2 grid of points across our entire study area, derived in the Create Fishnet tool in ArcGIS Data Management toolbox. These points were also attributed with 16 environmental predictor variables using the Extract Multi Values to Points tool in ArcGIS to which the scored predictions could be applied with their respective acoustic–environmental relationship at each point on the grid. We added the scored prediction data to a map of KENWR in ArcGIS. We used the Interpolate-to-Raster and Inverse Distance Weighting (IDW) tools in ArcGIS Spatial Analyst to create a continuous map indicating the spatial distribution of snowmobile noise and natural quiet across our study area.

We interpreted the accuracy of our models by calculating the normalized root mean squared error (nRMSE). The nRMSE is expressed as the percent error between predicted values of soundscape power and observed values where a lower percentage indicates higher prediction accuracy. We considered an nRMSE of ≤20% (i.e., ≥80% accuracy) to be a relatively accurate model of snowmobile noise and natural quiet soundscape power given the scale of our study area (800,000 ha). These steps resulted in two models that display the spatial distribution of snowmobile noise and natural quiet throughout KENWR with a measured accuracy.

Table 1. Spatial layers used as variables to generate spatially explicit predictive models of and acoustic–environmental relationships with snowmobile noise and natural quiet in Kenai National Wildlife Refuge, Alaska.

Variable	Abbreviation
Distance to conifer forest	CON
Distance to deciduous forest	DEC
Distance to lakes	LAK
Distance to oil and gas compressors	OIL
Distance to rivers	RIV
Distance to roads	ROD
Distance to seismic lines	SEI
Distance to shrub land	SHR
Distance to snowmobile trails	SMT
Distance to urban areas	URB
Distance to wetlands	WET
Aspect	ASP
Elevation	ELE
Slope	SLO
Snow depth[a]	SNO
Snowmobile activity[a]	SNM

[a] Derived from GIS predictive models (Mullet 2014)

Sound Analysis

We used Minitab v16 (Minitab, State College, PA, USA) to summarize, graph, and analyze the soundscape power of snowmobile noise and natural quiet. We treated the audio recordings from each sound station as a temporal and spatial sample of snowmobile noise and natural quiet. We then summarized the information as the weighted average of soundscape power of each target variable for the entire study area. Our analysis focused on the weighted average of soundscape power of snowmobile noise and natural quiet to account for the other sources of sound in the form of geophony and technophony that did not define the subjects of our study. We expected the weighted average to provide a more accurate representation of soundscape power given the proportion of sound recordings of snowmobile noise emissions and natural quiet identified at each sound station.

We calculated and visualized soundscape power within each frequency for snowmobile noise and natural quiet and visualized the temporal variation of comparable frequency intervals for these target variables over 24-hr and monthly timeframes. Preliminary analysis revealed that soundscape power of snowmobile noise predominantly occurred in the 1–2 kHz frequency interval and was, therefore, the most representative frequency interval of snowmobile noise. Based on this finding, we used the soundscape power of natural quiet in the 1–2 kHz interval as a comparison with that of snowmobile noise.

We used a Pearson correlation test to determine if the weighted average soundscape power of snowmobile noise and natural quiet were correlated over 24-hr and monthly time frames ($\alpha = 0.05$). We calculated 95% confidence intervals (CI) to determine the differences in soundscape power between frequency intervals and the weighted-average soundscape power of snowmobile noise and natural quiet between months.

Quantifying the Area of Snowmobile Noise and Natural Quiet in Wilderness

To quantify the acoustic footprint of snowmobile noise in Wilderness and the proportion of natural quiet refugia, we reclassified the predicted soundscape power values of our models into two categories based on the 1st and 3rd quantiles of soundscape power of each target variable. We classified hotspots of snowmobile noise as the predicted soundscape power values in the upper 3rd quantile of our snowmobile noise model and classified natural quiet refugia based on the lowest 1st quantile range of predicted soundscape power from our natural quiet model. The reclassified raster of each model was then converted to polygons and clipped to the KENWR and CW layers in ArcGIS. We calculated the area (ha) of snowmobile noise hotspots and natural quiet refugia in CW and non-CW using the Calculate Geometry tool in ArcGIS. These calculations provided us with the area of CW affected by snowmobile noise (acoustic footprint) and the areas where natural quiet refugia were distributed.

RESULTS

Frequency and Temporal Characteristics of Snowmobile Noise and Natural Quiet

Over the course of our study from December to April, snowmobile noise constituted 5% of sound recordings (1259 records) in CW and 1% of sound recordings (324 records) in non-CW. However, snowmobile noise contributed 27% of technophony recordings in CW next to airplanes and automobile noise emitted from vehicles traveling along roads bordering the Mystery Creek Wilderness Unit (Figure 2). Recordings of natural quiet made up 70% (19,111 records) of CW sound recordings and 62% (20,157 records) of non-CW.

The average soundscape power of snowmobile noise was highest in the 1–2 kHz interval (0.9253 normalized watts/kHz). Soundscape power at frequency intervals between 2 and 11 kHz was considerably lower when visually compared to the 1–2 kHz interval (Figure 3). However, soundscape power at the 2–3 kHz interval was higher than all subsequent frequencies. Soundscape power gradually decreased from 0.2266 normalized watts/kHz at the 2–3 kHz interval to 0.0400 normalized watts/kHz at the 10–11 kHz interval (Figure 3).

Average soundscape power by frequency interval of natural quiet was highest within the 1–2 kHz interval (0.0122 normalized watts/kHz) but significantly lower (95% CI 0.0112, 0.0132) than that of snowmobile noise (95% CI 0.9143, 0.9363). Values of soundscape power at frequency intervals between 2 and 8 kHz were relatively higher than those for intervals 8–11 kHz (Figure 3).

Our analysis of daily patterns of soundscape power revealed that snowmobile noise occurred predominantly during daylight hours from 0900 to 1900 hrs, peaking between the hours of 1300 and 1500 (Figure 4). Lower soundscape power values of natural quiet, with consideration to the temporal variation of soundscape power for geophony and technophony, were consistent with evening time intervals between 2200 and 0400 hrs, reaching its lowest values between 0000 and 0200 hrs (Figure 4). We found that natural quiet soundscape power was significantly inversely correlated with snowmobile noise over 24-hr time periods (Pearson = −0.880, $p = 0.000$).

On a monthly timeframe, the weighted average of soundscape power for snowmobile noise was significantly higher for February (95% CI 0.040, 0.061) and March (95% CI 0.030, 0.050) than December (95% CI 0.008, 0.013) and January (95% CI 0.012, 0.024) and marginally higher than April (95% CI 0.006, 0.031) (Figure 5). Conversely, when considering the temporal variation of technophony and geophony, the weighted average of soundscape power of natural quiet in January was significantly lower (95% CI 0.145, 0.155) than all other months, whereas the weighted average of soundscape power for March was significantly lower (95% CI 0.340, 0.355) than December (95% CI 0.398, 0.414), February (95% CI 0.565, 0.579), and April (95% CI 0.507, 0.536) (Figure 5). We found no correlation between soundscape power of snowmobile noise and natural quiet over monthly timeframes (Pearson = −0.377, $p = 0.532$).

Acoustic Footprint of Snowmobile Noise

The snowmobile noise model had a relatively low error (nRMSE = 16.3%). Distance to rivers, lakes, wetlands, and level of snowmobile activity (tracks/0.06 km^2) were the top four most important environmental predictors of snowmobile noise (Table 2). Soundscape power predictions of snowmobile noise were highest when they occurred ≤250 m from rivers, >1800 m from lakes, <500 m from wetlands, and in areas where snowmobile activity exceeded seven tracks/0.06 km^2 (Figure 6).

The 3rd quantile of snowmobile noise was 0.9756 normalized watts/kHz (max = 0.9945; min = 0.7401; median = 0.9525; 1st quantile = 0.9250). High predictions of soundscape power from snowmobile noise extended across 98,583 ha (39%) of CW where snowmobiles are permitted, 18% of all CW including areas where snowmobiles are prohibited and permitted under management conditions (Figure 7; Table 3). High predictions of soundscape power from snowmobile noise were also projected to 11,807 ha of CW areas where snowmobiling is prohibited, specifically along the western boundary of prohibited areas of the Kenai Mountains where access by rivers and wetlands extend beyond permitted regions (Figure 7; Table 3). Approximately 44% (118,036 ha) of the KENWR open to snowmobiling outside CW (270,229 ha) was predicted as snow-

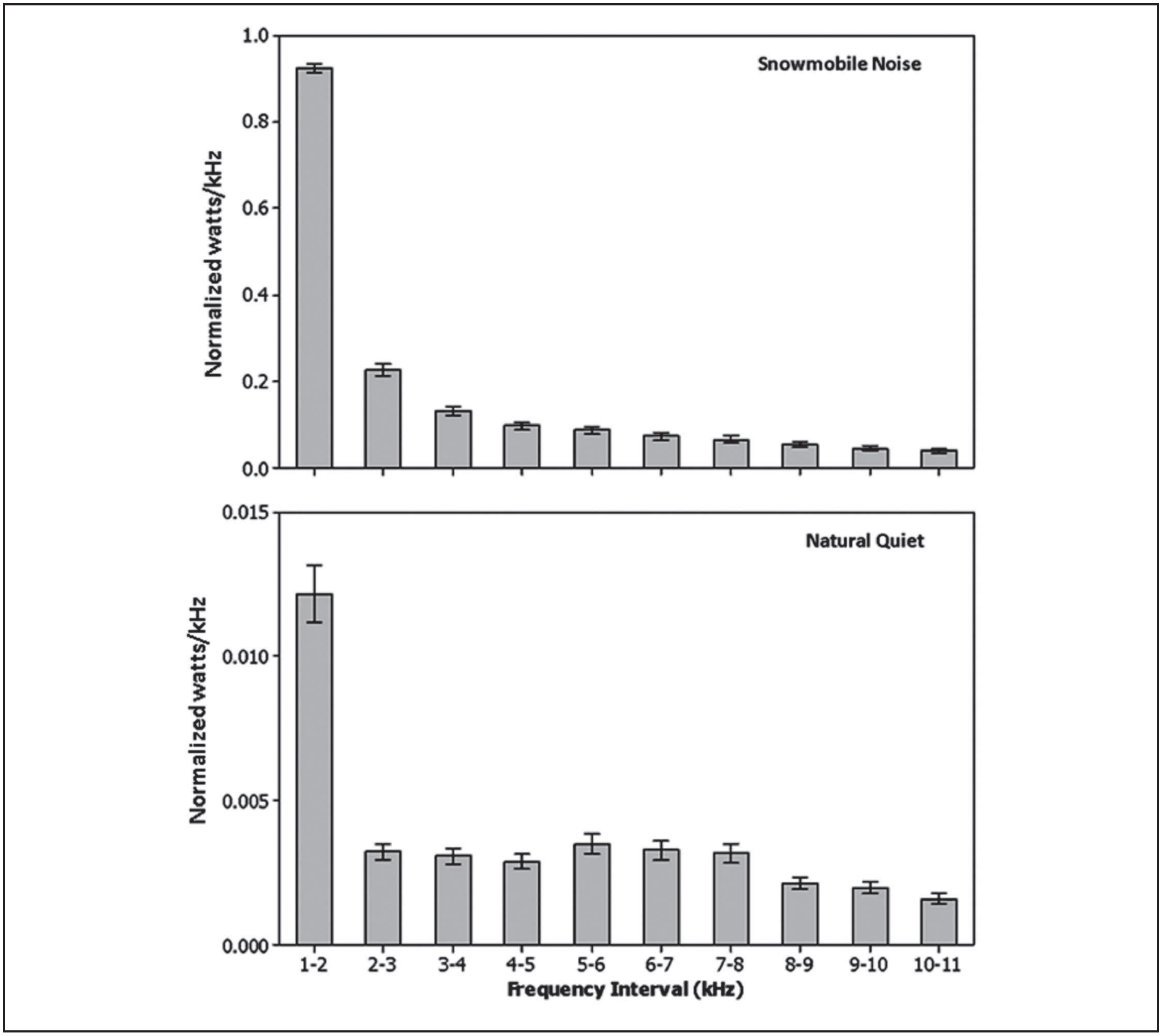

Figure 3. Average soundscape power (normalized watts/kHz) and 95% confidence intervals within ten 1-kHz frequency intervals summarized for snowmobile noise and natural quiet identified from 59,598 sound recordings acquired over winter (December 2011–April 2012) in Kenai National Wildlife Refuge, Alaska.

mobile noise hotspots (Figure 7; Table 3).

Natural Quiet Refugia

Our natural quiet model had an nRMSE of 9.1%. Distance to snowmobile trails, rivers, and snowmobile activity levels were the top three most important predictors of natural quiet (Table 2). Natural quiet occurred most often in areas that were >20 km from snowmobile trails, >500 m from rivers, and in areas with <9 snowmobile tracks/0.06 km^2 (Figure 8).

The 1st quantile of natural quiet was 0.4935 normalized watts/kHz (max = 0.7461; min = 0.3897; median = 0.5116; 3rd quantile = 0.5521). Natural quiet made up 90,385 ha (36%) of CW open to snowmobiling, 179,604 ha (64%) of CW where snowmobiling is prohibited (281,158 ha), and 269,989 ha (51%) of all CW (Figure 7; Table 3). Over 33% (29,733 ha) of the quietest areas in CW officially open to snowmobiling were inaccessible by snowmobile due to dense coniferous forest and because some large lakes did not entirely freeze during our study. Approximately 48% (128,521 ha) of natural quiet in all CW was within areas inaccessible to (e.g., unfrozen lakes, dense coniferous forest) or prohibited from snowmobiling. Natural quiet refugia consisted of 47,873 ha (18%) of the total area open to snowmobiling outside CW (Figure 7; Table 3).

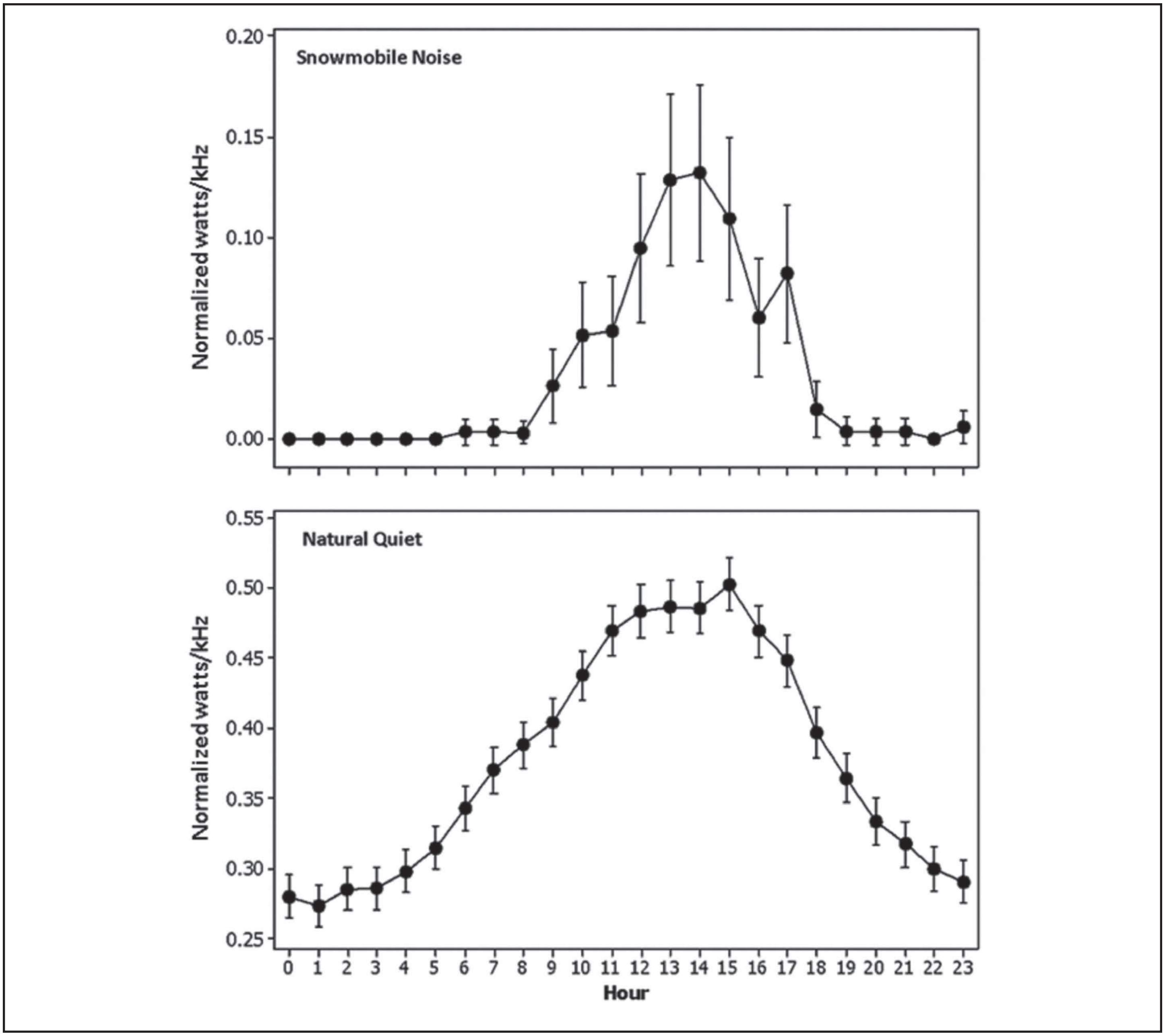

Figure 4. Weighted average soundscape power (normalized watts/kHz) and 95% confidence intervals of snowmobile noise and natural quiet over a 24-h time period during winter (December 2011–April 2012) in Kenai National Wildlife Refuge, Alaska. Time 0 is 12:00 a.m. and 23 is 11:00 p.m. The *y*-axis for each sound component is not the same scale in order to reflect variation. Natural quiet is represented by low values of soundscape power while high values represent the combination of all technophony and geophony sound sources.

DISCUSSION

Snowmobiles travel across and compress the snow surface, thereby leaving distinct impressions on the landscape. Snow compressed by snowmobiles thaws much later than uncompressed snowpack and can lead to direct impacts to soil and vegetation (Neumann and Merriam 1972; Mullet 2014). Although these imprints are often localized, the technophony snowmobiles emit extends beyond the physical tracks they leave on the landscape. We found that snowmobiles accessing CW in KENWR throughout the winter of 2011–2012 had a large acoustic footprint, affecting over a third of CW where they are permitted and to a smaller, but meaningful extent, 11,807 ha of CW where they are prohibited.

We found that snowmobile noise had substantially higher soundscape power within the 1–2 kHz frequency interval than that of natural quiet sound recordings. This evidence is consistent with the findings of Gage and Axel (2014) and Mullet et al. (2016) who found that a majority of technophony lies within the low frequency range <2000 Hz. Although soundscape power of natural quiet was lower than that

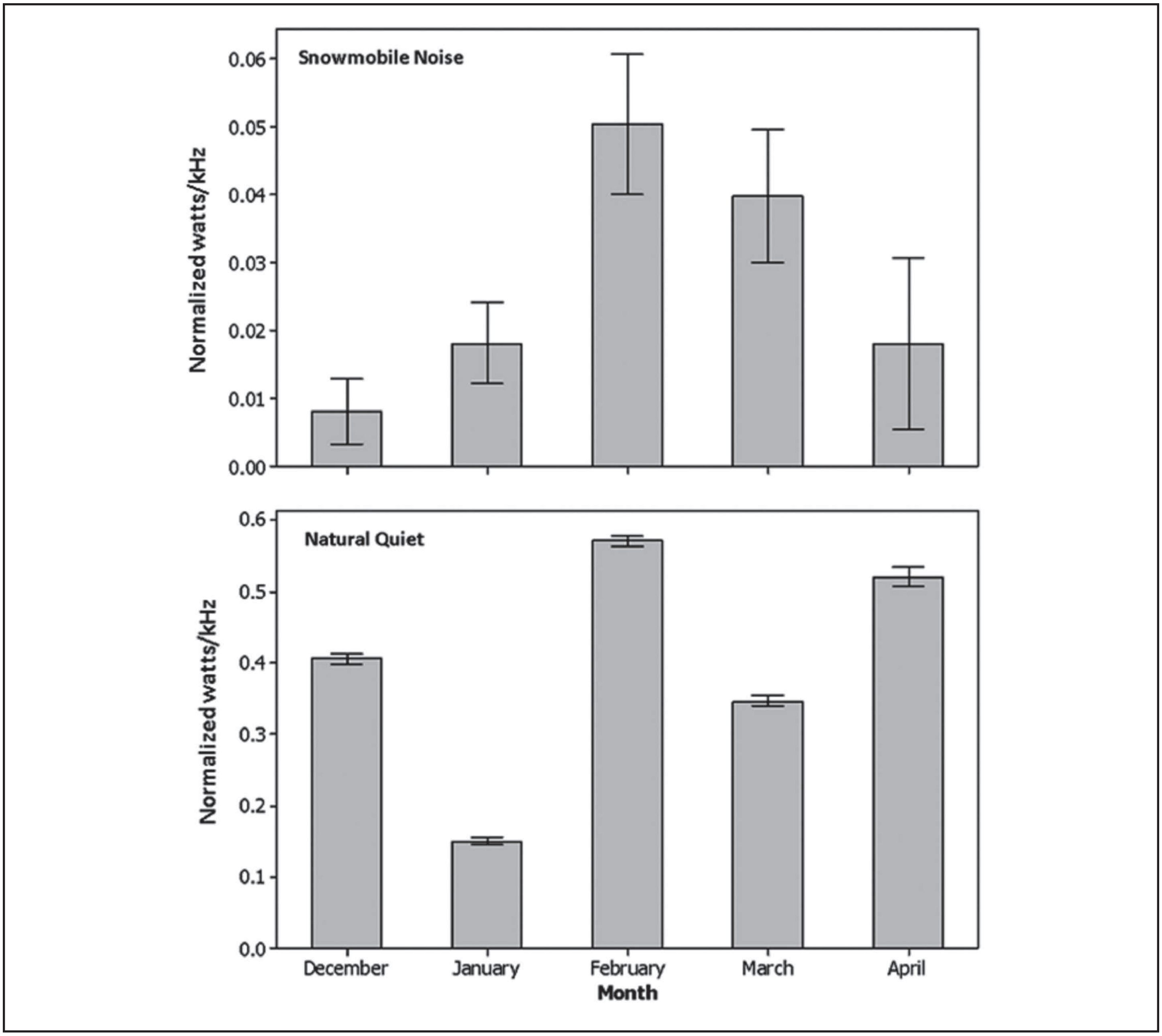

Figure 5. Weighted average soundscape power (normalized watts/kHz) and 95% confidence intervals of snowmobile noise and natural quiet over the months of winter (December 2011–April 2012) in Kenai National Wildlife Refuge, Alaska. The *y*-axis for both soundscape components is not the same scale in order to reflect variation. Natural quiet is represented by low values of soundscape power while high values represent the combination of all technophony and geophony sound sources.

of snowmobile noise, a majority of soundscape power was still within the 1–2 kHz interval. This frequency interval included the low-frequency vocalizations produced by corvid species like the Common Raven and Gray Jay (*Perisoreus canadensis* L.), common and abundant winter residents, and the low-frequency sounds of subtle wind events. The higher-frequency calls of other winter resident passerines were within the 2–8 kHz frequency intervals, e.g., Black-capped Chickadee and Common Redpoll (*Carduelis flammea* L.). Gage and Axel (2014) and Mullet et al. (2016) documented similar observations by comparing identified sound sources with their soundscape power within frequency intervals discernable in spectrograms.

Over 24-hr timeframes we found that snowmobile noise and natural quiet were inversely correlated. Snowmobile noise occurred during daylight hours whereas natural quiet occurred most often at night. This result was expected because human activity and use of machines is more common during the day (Brown et al. 2009). Also, daylight provides visibility and safer traveling conditions for snowmobilers. Similarly, the overall decline in human

Table 2. Rank of importance of environmental variables associated with the spatial distribution of snowmobile noise and natural quiet in Kenai National Wildlife Refuge, Alaska, over winter (December 2011–April 2012).

Rank	Snowmobile noise	Natural quiet
1	RIV	SMT
2	LAK	RIV
3	WET	SNM
4	SNM	OIL
5	SMT	URB
6	SHR	ELE
7	ELE	LAK
8	SLO	WET
9	SEI	DEC
10	OIL	SHR
11	ROD	SEI
12	ASP	CON
13	SNO	SNO
14	DEC	ROD
15	URB	SLO
16	CON	ASP

and wildlife activity at night, typical of species in our study area during winter (Daan and Aschoff 1975; Brown et al. 2009; Marchand 2013), would result in quieter time periods. However, through the identification of sound sources within individual sound recordings, we found that diurnal periods of natural quiet did occur but to a lesser extent than all other sound sources.

Over monthly intervals, soundscape power of snowmobile noise was significantly higher during February and March than December, January, and April. This detection in snowmobile activity through acoustic monitoring coincides with the monthly variation in snow depth over the same time period throughout KENWR coupled with increases in daylight hours and relatively warmer temperatures (unpub. data). These factors may have provided more favorable conditions for snowmobiling than those observed during December, January, and April.

We also found that January had significantly lower soundscape power than all other months. The reason for this finding is not entirely known but parking lot surveys of snowmobiles entering KENWR revealed a noticeably lower number in January than all other months (unpub. data). Average ambient temperatures in January were also 23 °C lower than December and 27 °C lower than February, with 3 cm less snowfall. It is possible that the combination of climatic and snow conditions were less desirable for human activity and decreased wildlife activity and vocal behavior (Marchand 2013), resulting in a significant reduction in soundscape power. These findings are not dissimilar from those of Mullet et al. (2016) who found that all technophonic sound sources, including those not inhibited by snowfall (e.g., aircraft, automobiles), contributed higher soundscape power in December, February, and April throughout KENWR, while the lowest values of technophony were most commonly documented during January.

Snowmobile noise was associated with areas ≤250 m and ≤500 m from rivers and wetlands, respectively. The KENWR possesses over 563,000 km of rivers and approximately 1100 wetlands >1 ha. Considering rivers and wetlands in KENWR are predominantly frozen all winter and provide an open, unimpeded landscape for travel, they are both widely used by snowmobilers for accessing trapping and hunting sites, remote cabins, and for recreation not related to these activities. Our models reflect the common use of these landscape features that are likely providing exceptional access to remote regions where snowmobile noise can extend to much larger areas of CW.

Not surprisingly, we found that snowmobile noise was strongly associated with snowmobile activity levels >7 snowmobile tracks/0.06 km^2. This provides confirmatory evidence that soundscape power of snowmobile noise increases in areas with increasing snowmobile activity. This relationship may be indicative of group-related snowmobile activity associated with recreational riding.

Interestingly, snowmobile noise was strongly associated with areas >2 km from lakes. Although frozen lakes often serve as travel corridors for snowmobilers to other locations throughout KENWR, our models do not indicate that the distribution of snowmobile noise and lakes coincide. This can be partially explained by the fact that 56% of the 1850 lakes in KENWR's CW are in areas where snowmobiling is prohibited, mainly in the northern lowlands. However, Van Renterghem et al. (2007) found that the topography of mountainous regions, like those surrounding lakes in the southern regions of KENWR, increase the audibility of technophony farther from the source more so than that in flat terrain environments (e.g., lakes). Both conditions may explain the spatial diversity of high soundscape power of snowmobile noise in areas farther from lakes in snowmobile-restricted non-mountainous regions of the north (i.e., Dave Spencer Wilderness Unit) and unrestricted mountainous regions surrounding lakes in the south (i.e., Andrew Simons Wilderness Unit) of KENWR.

Natural quiet was prevalent in 51% of CW. Approximately a third of natural quiet areas in CW open to snowmobiling were predicted on Tustumena Lake, the largest lake on the Kenai Peninsula. Tustumena Lake is only accessible to snowmobiling on ice along its margins and only partially throughout the open season due to melting conditions in late winter. Furthermore, nearly half of natural quiet areas in all CW

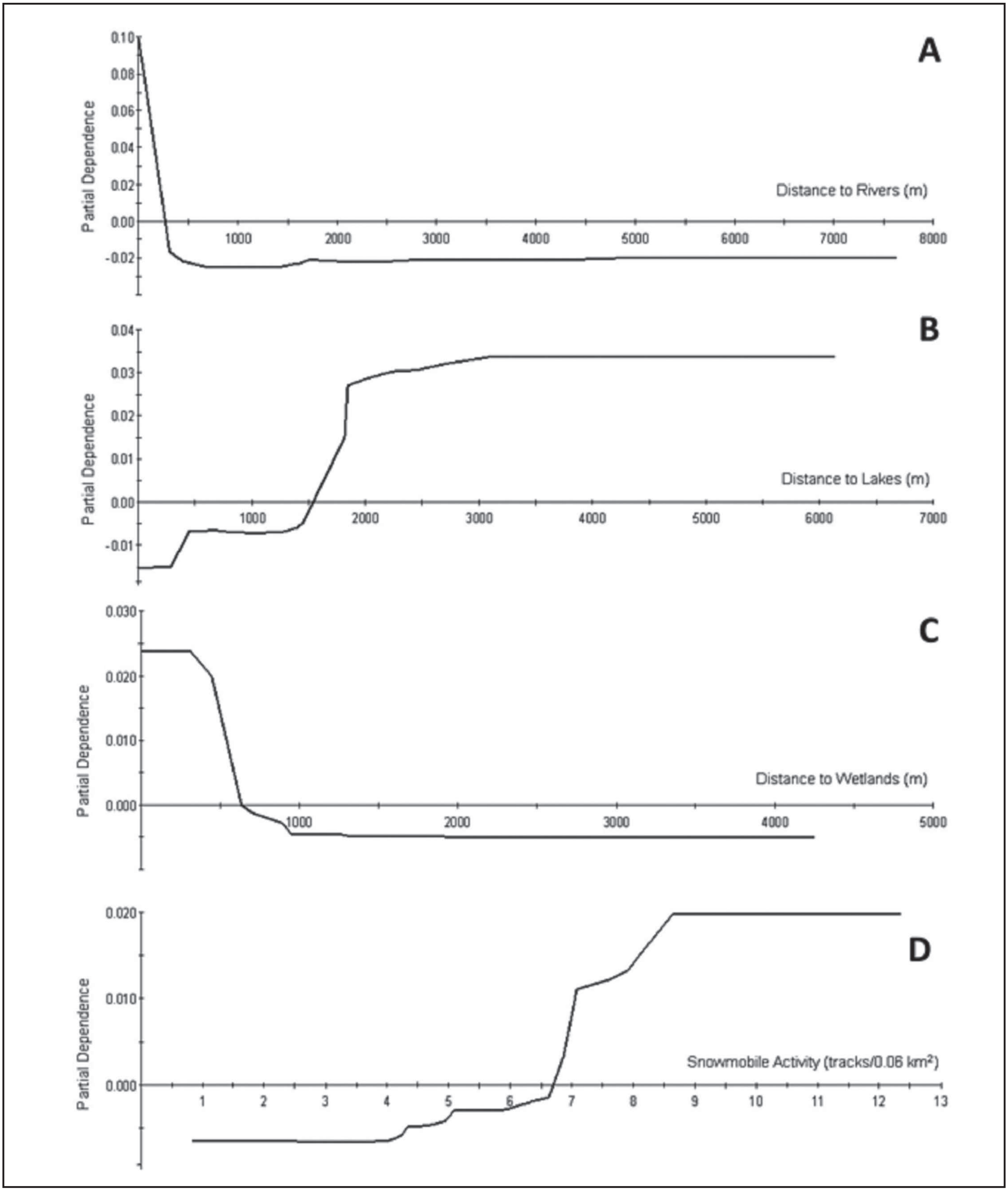

Figure 6. One predictor dependence for the top four environmental variables displaying their acoustic–environmental relationships with snowmobile noise in the Kenai National Wildlife Refuge (December 2011–April 2012): (A) distance to rivers, (B) distance to lakes, (C) distance to wetlands, and (D) snowmobile activity.

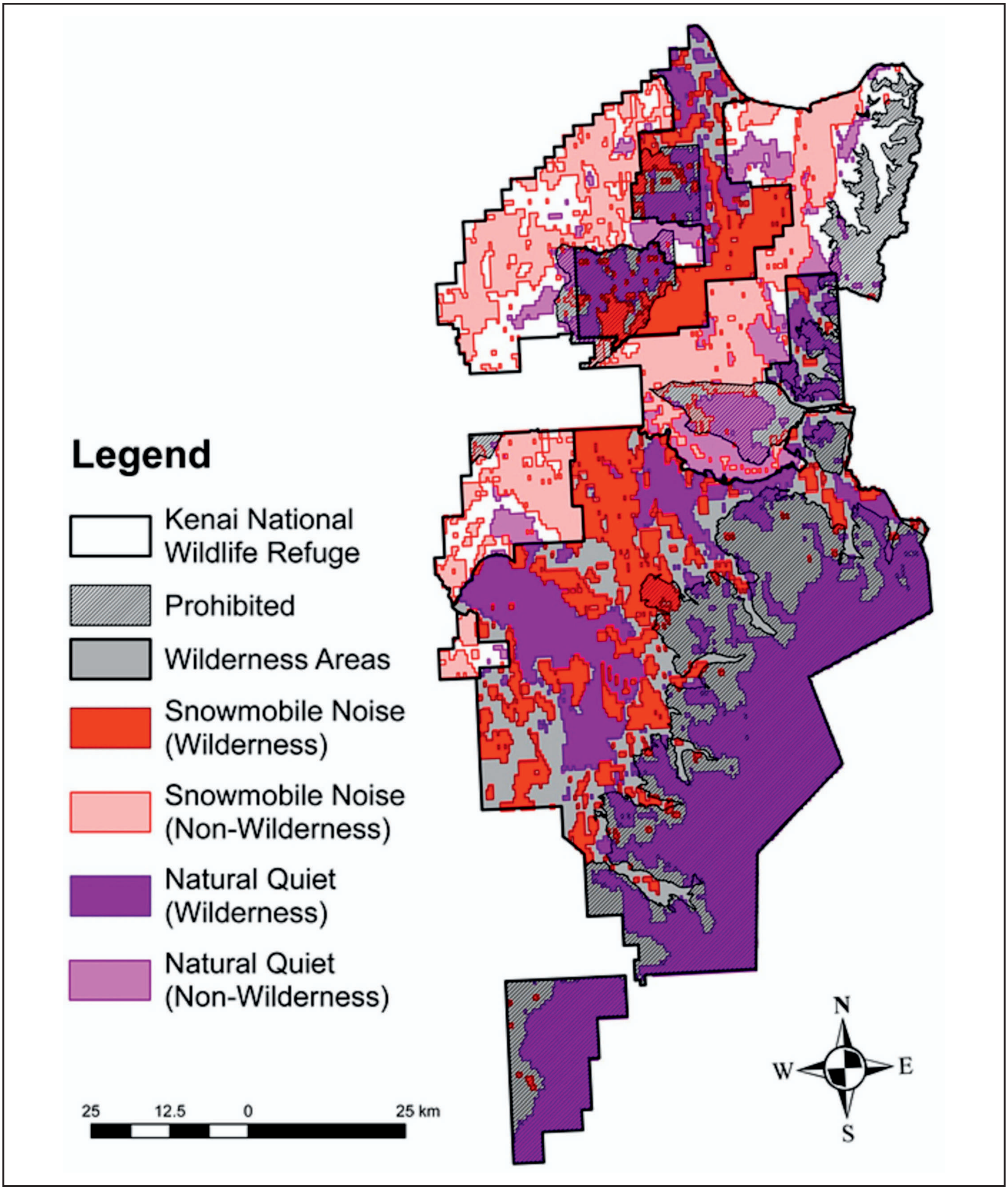

Figure 7. Predicted spatial distribution of the acoustic footprint of snowmobile noise and natural quiet refugia in the Kenai National Wildlife Refuge, Alaska, in relation to congressionally designated wilderness and areas where snowmobiling is prohibited.

Table 3. Area (ha) and percent of the acoustic footprint of snowmobile noise and natural quiet refugia in the Kenai National Wildlife Refuge, Alaska (KENWR), over winter (December 2011–April 2012).

		Snowmobile noise		Natural quiet	
Class	Total area	Area	%	Area	%
Non-Wilderness	270,229	118,036	44	47,873	18
Wilderness open to snowmobiling	253,191	98,583	39	90,385	36
Wilderness closed to snowmobiling	281,158	11,807	4	179,604	64
All Wilderness	534,349	98,583	18	269,989	51
All KENWR	804,751	216,619	27	317,862	39

were inaccessible due to dense coniferous forest or prohibited from snowmobiling that predominantly included the Harding Ice Field.

As expected, we found the spatial distribution of natural quiet refugia was inversely related to areas of snowmobile activity and the environmental variables associated with it. Natural quiet occurred predominantly in areas >20 km from snowmobile trails and >500 m from rivers, both of which are important linear features used by snowmobilers to access large portions of the KENWR's CW. Additionally, in areas where snowmobiling was not associated with rivers and trails, natural quiet was more prevalent where there was less snowmobile activity per unit area (i.e., <9 snowmobile tracks/0.06 km^2).

The acoustic–environmental relationships of snowmobile noise in CW suggest that some attributes of the landscape are more impacted than others, indicating a degradation of naturalness. Given that we isolated natural quiet sound recordings from all other sources of technophony, it is remarkable that the inverse correlation of natural quiet refugia with snowmobile-related landscape variables and activity were ranked more important than other variables indicative of natural areas (e.g., coniferous forest, deciduous forests). This is a strong indication that snowmobiling can profoundly influence soundscapes that would otherwise be natural quiet in the absence of snowmobiles.

The significance of these acoustic refugia is not entirely realized. However, we provide evidence that natural quiet phenomena are still present and spatially prolific throughout CW areas in KENWR despite the popularity of snowmobiling and other possible sources of technophony we did not cover in this analysis (e.g., aircraft). Furthermore, our findings suggest that prohibition of snowmobiling in specific areas of CW can preserve the characteristics of naturalness and opportunities for solitude as defined by the Wilderness Act.

Management Implications

Soundscape conservation is a growing focus on public lands in the United States (Miller 2008; Pilcher et al. 2009) as well as in endangered ecosystems around the world (Irvine et al. 2009; Dumyahn and Pijanowski 2011; Monacchi 2013). From a human perspective, natural quiet and soundscapes are important characteristics of the environment that a person uses to identify themselves with a sense of place, a desired condition for worship, meditation, and respect for the dead (Ehrenhaus 1988; Assagioli and Anglada 2013). Natural soundscapes and natural quiet are also known to initiate physiological responses in the body and mind creating a sense of relaxation and calm (Bjork 1986, 1995; Aarts and Dijksterhuis 2003; Cmiel et al. 2004). Natural quiet and the composition of the soundscape also have a significant influence on the behavior and distribution of wildlife (McDonald et al. 1995; Francis et al. 2009). All evidence shows that natural quiet areas are important for both human and wildlife experience that CW is intended to provide (Kariel 1990; McDonald et al. 1995).

Although soundscape conservation is slow to develop, the significance of natural soundscapes to human experience and wildlife has been considered a key component in conservation efforts by the NPS. The NPS has specifically identified natural soundscapes as a resource. Under the mandates of various Congressional acts and policies such as the Organic Act of 1916, National Parks Air Tour Management Act of 2000, the 2000 Director's Order #47 (Soundscape Preservation and Noise Management), and the 2006 Cultural Soundscape Management Policy, the NPS must manage natural soundscapes as a resource for ecological and human benefits.

The National Wildlife Refuge System (NWRS) lacks these mandates to specifically manage soundscapes. However, KENWR has a congressional mandate to preserve CW under the Wilderness Act while providing snowmobiling access under the overwriting provisions of ANILCA and ensuring that snowmobile practices are compatible with the mission of the NWRS under the 1966 NWRS Administrative Act, as amended. The ambiguous and otherwise undefined terminology of "traditional activities" in ANILCA provides no clear path for ensuring appropriate and compatible use of snowmobiles in CW. In our study, we clearly define areas of CW where the acoustic footprint of snowmobile noise affects its character across a broad spatial scale and, conversely, show areas of acoustic refugia from technophony during winter. Our findings indicate that the absence of snowmobile activity coincides with natural quiet, suggesting that the current activities and noise emissions of snowmobiles are impacting CW character.

Balancing the mandates of ANILCA and

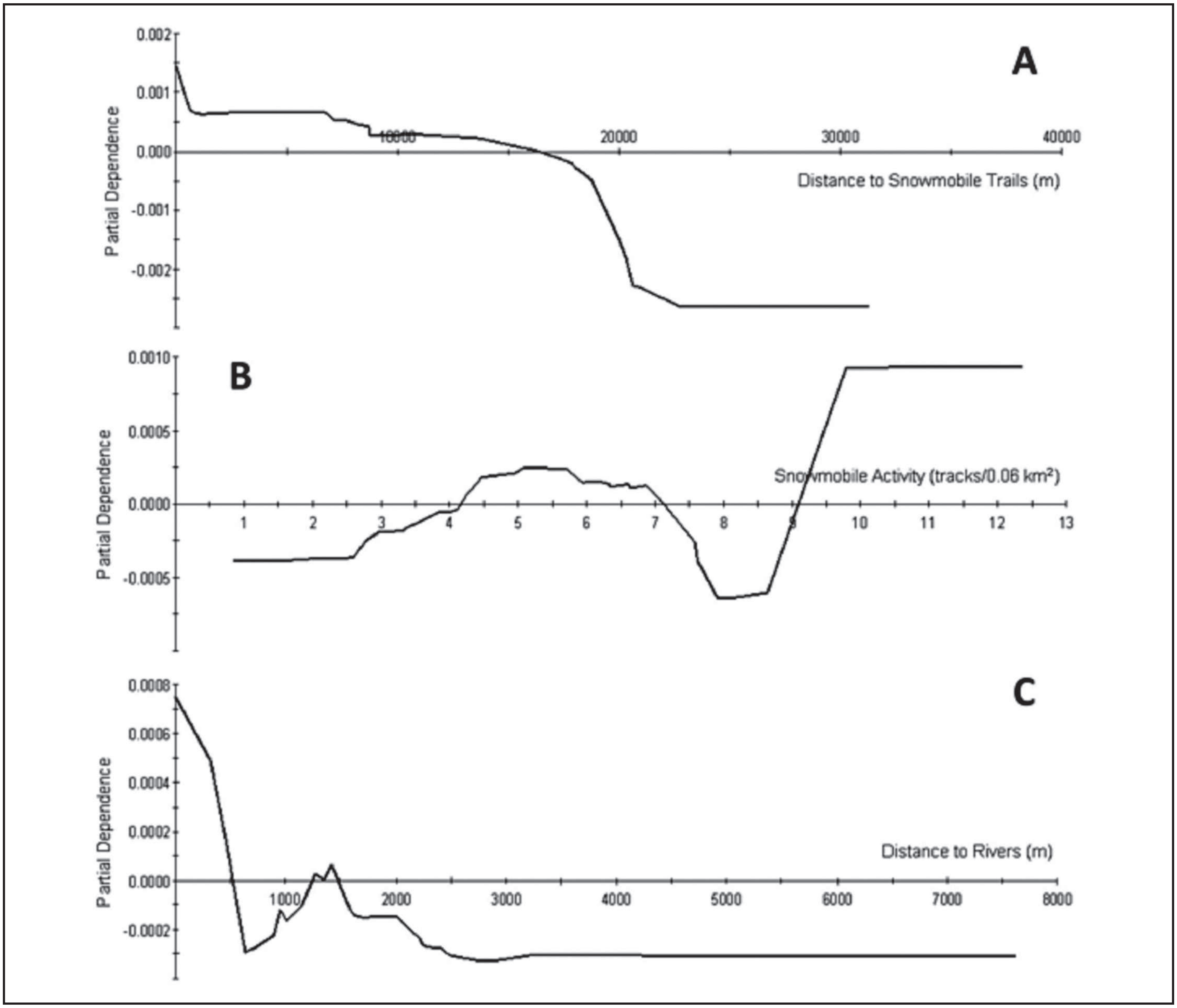

Figure 8. One predictor dependence for the top three environmental variables displaying their acoustic–environmental relationships with natural quiet refugia in the Kenai National Wildlife Refuge, Alaska (December 2011–April 2012): (A) distance to snowmobile trails, (B) snowmobile activity, and (C) distance to rivers. Lowest values are quieter.

the Wilderness Act is certainly challenging and demands creative management by KENWR. One option is to define "traditional activities" stated in ANILCA, an approach used by Denali National Park and Preserve that enables managers to specifically regulate recreational snowmobiling in CW to preserve natural qualities (CFR 36 Section 13.950) (Tranel 2001). Another option is to use the findings of our study to reconsider the criteria used to determine compatibility that currently allows snowmobiles on parts of CW when snow depth is adequate to minimize impacts to vegetation (West 2007). A third option is to specifically preserve areas of natural quiet within CW by prohibiting snowmobiles from areas of high risk and/or restricting the type of snowmobiles to the quieter 4-stroke and enhanced noise-suppressed 2-stroke motors now being manufactured (Miers et al. 2000).

The large acoustic footprint of snowmobiles in CW may have many broader ecological implications to this subarctic ecosystem not yet identified. Moreover, snowmobile activity is simply one source of technophony in the KENWR soundscape and it is seasonally restricted. Aircraft is a common and prolific source of technophony at all times of the year (Mullet 2014). Added to this, summer months not only exhibit an increase in aircraft activity, but also constitute the sounds of motorboats and

>1 million automobiles traversing roads through and around KENWR each year (Kenai National Wildlife Refuge 2010).

A study done in June 2004 and 2006 found that the A-weighted SPLs throughout KENWR ranged from 32 to 95 dBa, sound levels equivalent to those recorded in CW areas by the NPS (32–42 dBa; National Park Service 2000) and that of some manufacturing plants (86–93 dBa; Chang et al. 2013). Although we cannot yet assess the impacts these technophonic sources may have on CW in KENWR, we speculate that the acoustic refugia of natural quiet is likely reduced and perhaps spatially reconfigured as a result of increased machine-related activities in summer.

A large body of work has been accumulating on the subject of noise impacts on the behavior, communication, physiology, and reproductive success of terrestrial wildlife that significantly influences ecological processes (Creel et al. 2002; Reihndt 2003; Francis et al. 2009; Barber et al. 2010; Brumm 2010; Chan and Blumstein 2011; Ortega 2012; McClure et al. 2013). More recently, the field of ecoacoustics (Sueur and Farina 2015) is beginning to find evidence of noise impacts on soundscapes as a whole, rather than individual species (Duarte et al. 2015). However, the empirical evidence that shows noise impacts on bird communication and changes in the occupancy of sound-producing wildlife in noisy habitats suggests that natural soundscapes to which these species contribute are being considerably altered. We encourage further study to test hypotheses on this subject.

By applying the theories of ecoacoustics in the contexts of soundscape ecology, our methods and models provide several specific benefits to KENWR and more generally to other CW areas and wild lands in Alaska and other parts of the United States including (1) a baseline for monitoring future snowmobile activity, (2) a baseline for contrasting the spatial distribution and soundscape power of technophony and natural quiet in winter versus summer, and (3) the potential designation of focal areas to preserve the CW characteristics of naturalness and opportunities for solitude. Since the Wilderness Act was passed in 1964, the area of CW in the United States has grown from 3.6 million ha at its inception to 42.9 million ha today, of which more than half is in Alaska. Through ANILCA, lawmakers attempted to reconcile the public interest to preserve Alaska's landscapes and the many unresolved issues over native Alaskan land claims, subsistence lifestyle, energy development, economic growth, and transportation (Willis 1985). However, ANILCA's provisions that allow snowmobiling in CW are a degrading influence to its primeval character, the natural forces that shape its qualities, and the opportunities for human visitors to enjoy solitude in the absence of mechanization and technophony. While the legal gap remains, these negative effects will likely continue and possibly expand as snowmobiling increases with population growth.

ACKNOWLEDGMENTS

This study was funded by the US Fish and Wildlife Service, Kenai National Wildlife Refuge, and a research fellowship through the University of Alaska Fairbanks Graduate School. We appreciate the exceptional work by Ryan Park, Bennie Johnson, and Mandy Salminen, and the assistance of KENWR's staff. We thank Salford Systems Ltd. and Robin Tabone for the TreeNet license and technical support, respectively. We sincerely thank the reviewers of this manuscript for their helpful comments. Lastly, the findings and conclusions in this article are those of the authors and do not necessarily represent the views of any government agencies.

Timothy C. Mullet, PhD, received his doctorate at the University of Alaska Fairbanks where he focused his research on winter soundscape ecology and the impacts snowmobile activity and noise have on boreal ecosystems in south-central Alaska. He has since published several papers on soundscape ecology including a quantitative description of Kenai National Wildlife Refuge's winter soundscape in the Journal of Landscape Ecology, a chapter on modeling soundscapes with machine learning in the book Ecoacoustics, and a pioneering article in Biosemiotics introducing the Acoustic Habitat Hypothesis. He continues to work on soundscape topics and many other ecological projects in Alaska and elsewhere.

John M. Morton, PhD, has been the supervisory biologist at Kenai National Wildlife Refuge since 2002. He has broad experience in developing and implementing research and management during his 27-year career as a US Fish and Wildlife Service biologist with both Refuges and Ecological Services. Current interests include climate change adaptation, inventory and monitoring design, and the effects of human disturbance on wildlife.

Stuart H. Gage, PhD, is Emeritus Professor at Michigan State University. Stuart retired after about 30 years as Professor of Entomology. He received the University Distinguished Faculty Award and the University Outreach and Engagement Campus Fellow at Michigan State University. He developed and taught, with several of his colleagues, a multidisciplinary Earth System Science (Honors) course to help students understand the dynamics and function of the Biosphere. Stuart continues as Director of the Remote Environmental Assessment Laboratory (http://www.real.msu.edu). His research focuses on the application of ecological sensors, analysis of sensor observations, and cyber infrastructure. He collaborates with colleagues in the area of soundscape ecology, acoustic analysis, regional ecosystem simulation modeling, ecological synthesis, and data mining.

Falk Huettmann, PhD, is an interdisciplinary wildlife conservation landscape ecologist at the University of Alaska Fairbanks in the Biology and Wildlife Department, Institute of Arctic Biology. Together with his international students he runs various wildlife and habitat research projects almost worldwide in his EWHALE lab. His research interests focus on applied topics such as sustainability and wilderness. His research employs primarily geographic information systems, open access data mining and machine learning, and for finding relevant signals in complex spatial data. Falk and his team published over 170 peer-reviewed papers and six books

on those subjects, in addition to numerous online data sets for free public use.

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